Optimization of the fatigue behaviour of welded joints by means of shot peening
- a comparison of results on steel and aluminium joints

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Abstract

Efficient methods for improving the fatigue strength of welded joints are important especially if high strength materials are used in lightweight constructions. Experimental results on welded joints of high strength steels have shown, that the improvement of the fatigue strength due to shot peening will be the higher, the lower the sharpness of weld notches is. The conclusion is, that the most effective improving method is the combination of TIG-welding or TIG-dressing and addititional shot peening. However in welded joints of aluminium alloys an optimized shot peening procedure is more effective than in steel joints, because the notch geometry at the weld toe may be improved by shot peening. So the fatigue strength of conventional MIG-welded aluminium joints may be increased as high as in steels only by shot peening especially if different shot peening parameters are combined.

1. Introduction

The mostly important factor which is responsible for the magnitude of the fatigue strength of welded joints is the sharpness of the notch geometry at the weld toe. Consequently the fatigue strength of high strength steels or high strength aluminium alloys may be very low in relation to the base material, if the joints of these materials are welded conventional MAW or MAG and no post weld treatment method as shot peening is applied. Because the efficiency of the notches at the weld toe will be the higher, the higher the ultimate strength of the base material is /1, 2/ techniques for improving the fatigue strength become more important, if high strength materials are used for welded joints. In /5/ it could be shown, that improving techniques like TIG-dressing of the weld toe or shot peening of conventional MAW-welded joints may produce a significantly increase of the

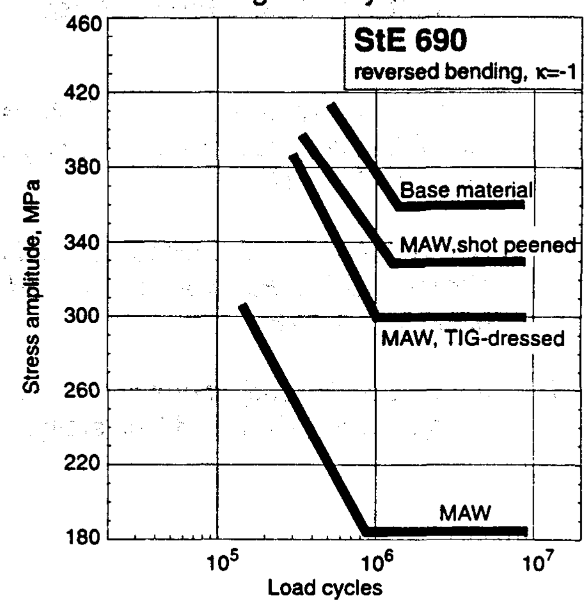

Figure 1: S-N-curves of butt welded joints of steel StE 690. MAW=Manual-Arc-Welding; TIG=Tungsten-Intert-Gas-welding /5/.

fatigue strength in relation to the as-welded state, but the fatigue strength will not reach the value of the base material (Fig.1).

Results on the combined application of special welding methods and mechanical surface treatment methods in order to improve the fatigue strength of high strength steels as high as possible have been published in /3,5/. In this paper, results of investigations conducted on the effects of various methods for improving the fatigue behaviour of welded joints of the aluminium alloys AlMg 3, AlMg 4.5 Mn and AlZn 4.5 Mg 1 are presented. The improvement of the fatigue strength, resulting from the application of special welding techniques or mechanical surface treatments, is verified by using the measured weld seam profiles, hardness and residual stress distributions and the results of metallographical investigations. Therefore, a comparison and an evaluation of the efficiency of the presented improving methods in steels and aluminium alloys is possible.

2. Experimental procedures

The weld seam improvement methods were realized in a simular way in steels and aluminium alloys. The notch sharpness of the weld toes was minimized by TIG-dressing of conventional MAW-or MAG- (steels) and MIG-welded (aluminium-alloys) joints. Furtehermore a flat weld seam was produced by TIG-welding of the cover passes (butt wlds) respectively of the last passes of cruciform welds. Steel shot S230 (steels) and austenitic steel shot (aluminium-alloys) in combination with glass beads was used for shot peening with the peening parameters described in /4,5/ to improve the fatigue strength. The investigations on aluminium alloys were carried out using cold formed Al-alloy AlMg 3 F21 (R_m= 210 MPa), cold formed and annealed Al-alloy AlMg 4.5 Mn G35 (R_m= 379 MPa) and age-hardened Al-alloy AlZn 4.5 Mg 1 (R_m= 407 MPa). The filler material used was S-AlMg 4.5 Mn for all alloys. Fig. 2 shows the different welded joints.

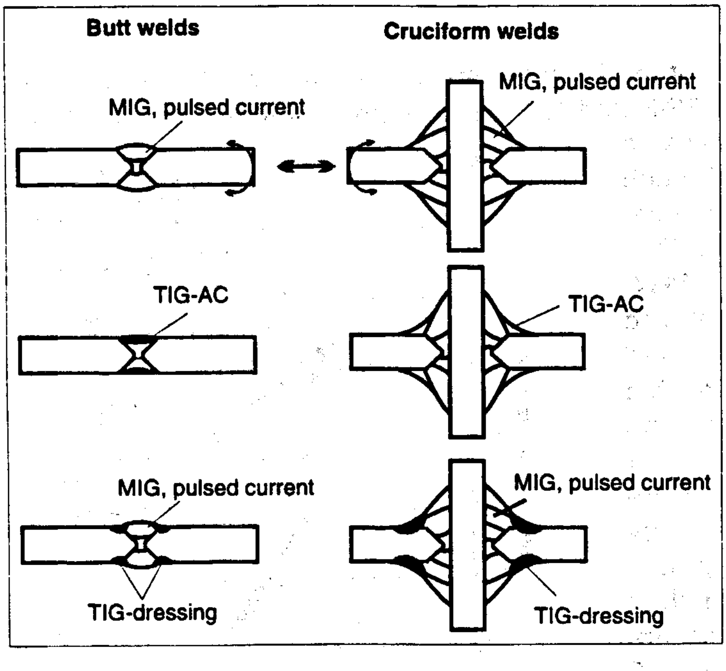

Figure 2: Investigated weldments and welding methods

The alloy AlZn 4.5 Mg 1 specimens was additionally age hardened after welding (100° C, 8h and 100° C, 20h). Shot peening was applied in the following two different ways. Various specimens were shot peened with austenitic steel shot (diameter between 0.58 and 0.82 mm, Almen-intensity 0.2...0.3 mm A2, coverage 200 %). Additionally a shot peening procedure was applied first using the steel shot as described and afterwards using a glass shot (diameter of 0.25 mm, Almen-intensity 0.2 mm A2, coverage > 150 %). MIG-welded joints of the alloy AlMg 4.5 Mn were first shot peened with glass shot, while the weldments of the alloy AlZn 4.5 Mg 1 were shot peened with the steel shot first.

Fatigue tests were performed under reversed bending and, in special cases, under push- pull-loading. A minimum of six specimens was tested under four different stress amplitudes to determine the fatigue strength of the different series of specimens. The S-N- curves were established by using the $\arcsin\sqrt{P}$-transformation for a fracture probability of 5 %, 50 % and 95 % with a limiting number of 10^7 load cycles. A horizontal line in the S-N-curves could be determined only for the alloys AlMg 3 and AlMg 4.5 Mn. The S-N- curve for load cycles > 10^7 of the alloy AlZn 4.5 Mg 1 was determined using half the slope of the endurance strength line.The fatigue test results were verified by residual stress measurements by means of X-rays, hardness measurements, metallographic investigations and the characterization of the crack initiation sites. The weld seam geometry was measured in order to estimate the notch factor α_k, with the aim of a comparison between the influences of the various welding and post-weld treatment methods and their effects on the fatigue strength.

3. Experimental results

Fig. 2 shows the results of the fatigue tests carried out on different butt welds of the high strength steels St 52-3 and StE 690, as presented in /3,5/. It could be shown that shot peening as well as a weld seam improvement through TIG-welding with a very flat weld seam profile (Fig. 2) or through TIG-dressing of conventional MAW-welded joints results in an improved fatigue strength. Under reversed bending the improvent due to shot peening is slightly higher than the improvement due to TIG-welding or TIG-dressing as shown in fig.3, whereas the weld seam improvement by TIG-welding or TIG-dressing produces a higher fatigue strength than shot peening, if the specimens are push-pull loaded. However, Fig. 2 indicates, that an optimized fatigue strength (under push-pull loading as well as under reversed bending) could only be reached by the combination of both methods. Then, the

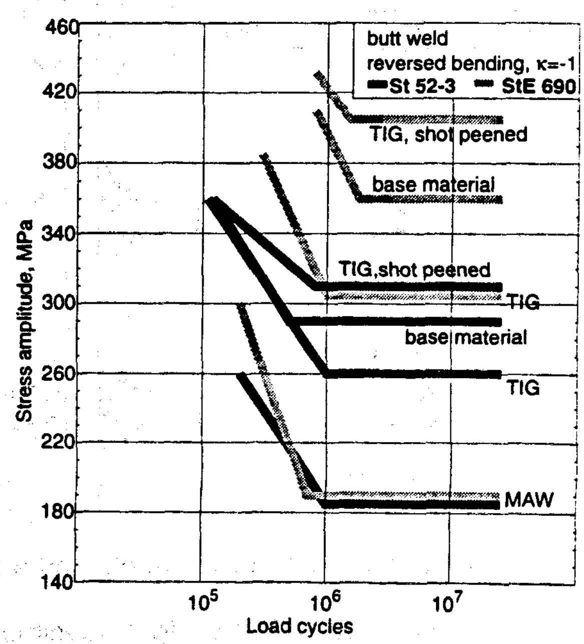

Figure 3: S-N-curves of butt welded joints of steel St 52.-3 and StE 690 after TIG-welding and after different post-weld treatments /3,5/.

fatigue strength of the welded joints is higher than the fatigue strength of the unpeened base material and this is an important advantage in the application of high strength steels, such as StE 690.

The fatigue strength of the butt welded AlMg 4.5 Mn-joints (Fig. 4) increases with a decrease in the sharpness of the notches at the weld toe, where the fatigue strength corresponds very well with the notch factor α_k. The consequence is that the fatigue strength of the TIG-welded joints is between 40 % and 65 % (steels) or 115 % (Al-alloys) higher than that of conventional MAW- (steels) or MIG-welded (Al-alloys) joints. The fatigue strength of the high strength steel cruciform welded joints may be approximately 70 % higher than that of the conventional MAW-welded joints. The fatigue strength of cruciform welded joints of the investigated Al-alloys increases also in the order (lowest to highest): MIG-welded with pulsed current, manual TIG-AC-welded and mechanized TIG-AC-welded.

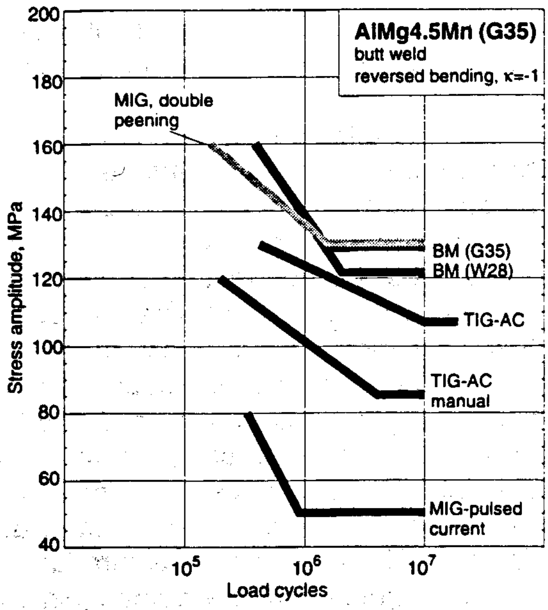

Figure 4: S-N-curves of butt weld ed joints of Al-alloy AlMg 4.5 Mn TIG-/MIG-welding and after different post-weld treatments (BM=base material)

The weld seam profile of the conventional steel and Al-alloy weld joints is improved through TIG-dressing. The notch factor decreases, causing the fatigue strength of both materials to reach the same fatigue strength as the mechanized TIG- butt welded joints. Therefore, for economical reasons, it may be better to use mechanized TIG-welding for the cover passes or for the last load carrying passes of cruciform welds because the weld seam profile will be just as good as after an additional post-weld treatment.

The fatigue strength of welded joints with an improved weld seam profile will be lower than the fatigue strength of the base material. The reason for this is that in steels the macroscopic notch of the weld toe is reduced, but the microscopic notches, such as nonmetallic inclusions at the weld toe, are more effective then and, especially in high strength steels, reduce the possible fatigue strength. In cold formed or age-

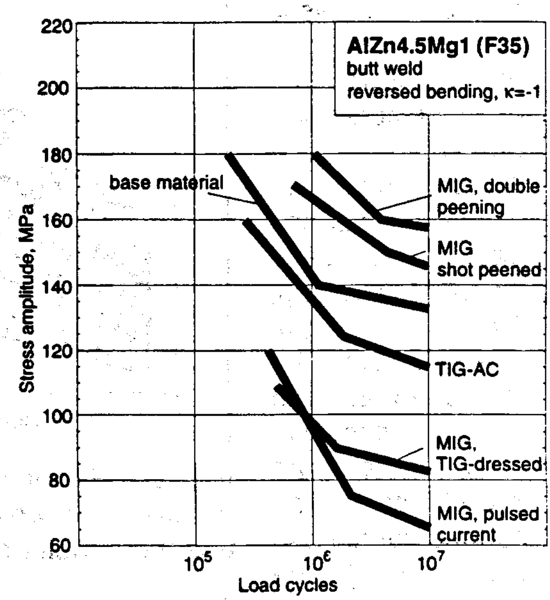

Figure 5: S-N-curves of butt welded joints of Al-alloy AlZn 4.5 Mg 1 TIG-/MIG-welding and after different post-weld treatments.

hardened Al- alloys (Fig. 5), a softened zone with a reduced ultimate strength which can be effective as a structural notch occurs within the weld zone or near the weld seam. Consequently the fatigue strength can not reach the value of the annealed base material. Other secondary factors which have an influence on the fatigue strength of both materials are the dendritic structure of the weld material and the magnitude and distribution of the tensile residual stresses as a result of welding.

The effects of shot peening are different in steels and Al-alloys. The fatigue behaviour of steel weldments as welded and after different post-weld treatments can be summarized with Fig.6. As shown the fatigue strength of welded steel joints can be improved by shot peening as much as by TIG-dressing (approximately 50 %...70 %), but the reached fatigue strength is always lower than the fatigue strength of the unpeened base material. The improvement of the fatigue strength of the steel St 52-3 welded joints, that is to say in lower strength steels, through shot peening is to a certain degree also a consequence of the work hardening of the surface, whereas in high strength steels, such as StE 690, the improvement of the fatigue strength is mainly a result of the compressive residual stresses at the surface induced by shot peening. The compressive residual stresses are obviously able to reduce the efficiency of the macroscopic notches at the weld toe to the same degree as TIG-dressing. However, the maximum fatigue strength in both steels can only be reached after shot peening of the welded joints with an improved weld seam profile. This means that an optimization of the fatigue strength (when the fatigue strength of the welded joints reaches the fatigue strength of the base material) requires, at first, a minimization of the macroscopic notches. Then, secondary effects as structural inhomogeneities, microscopic notches and tensile residual stresses can be completely compensated through cold work hardening of the surface and/or the compressive residual stresses induced by shot peening. The consequence of this is that after a combined application of weld seam improvement methods and mechanical surface treatments, such as shot peening, the fatigue strength can be increased as high as possible. Furthermore the importance of the surface roughness produced by the shot peening process has to be considered in high strength steels. The consequence is, that for an optimized fatigue strength of high strength steels a combination of different shot peening processes as shot peening with a steel shot with a hardness, which is high enough to produce an optimized state of the surface residual stresses,

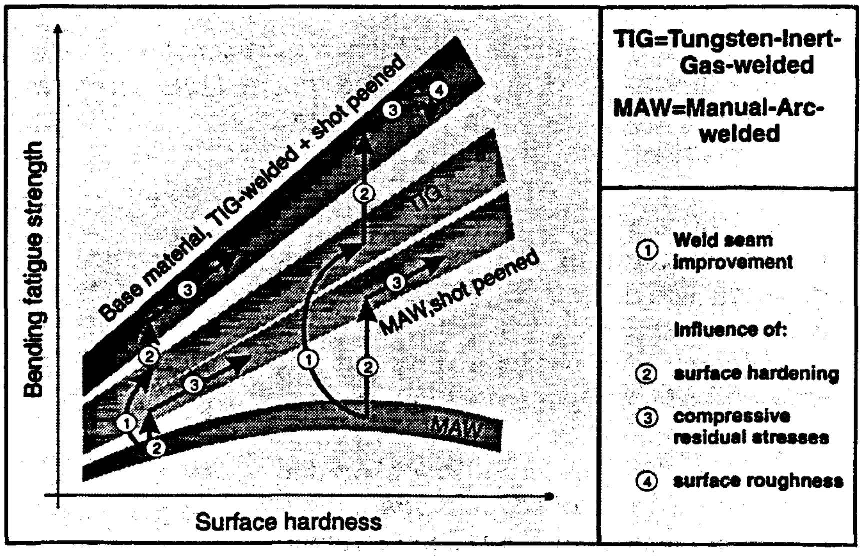

Figure 6: Relation between the fatigue strength and the surface hardness of weldments and influence of different post-weld treatment methods on the the increase of the fatigue strength.

and additional shot peening with glass beads to reduce the surface roughness, as applied in these investigations, is required.These conclusions are applicable on butt welded joints and cruciform welded joints, too.

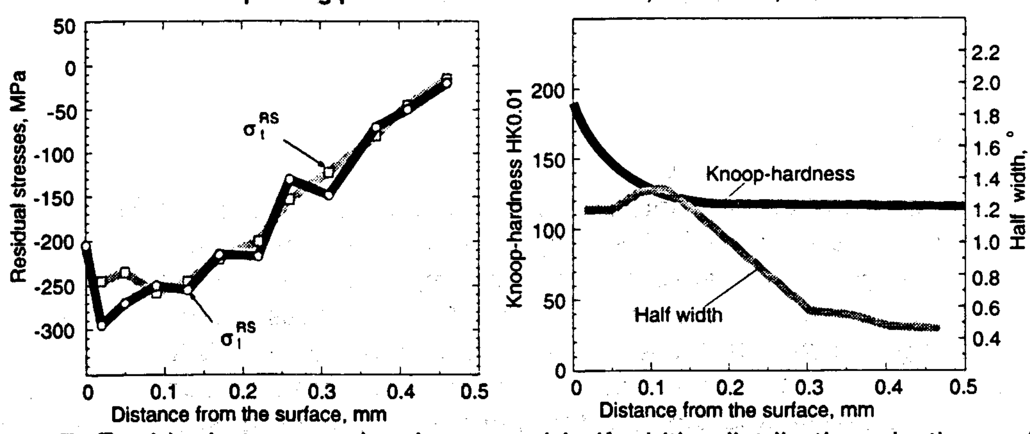

Figure 7: Residual stresses, hardness and half width- distributions in the surface layers of butt welded joint of AlMg 4.5Mn-alloy after combined shot peening.

As shown in Fig. 5, the fatigue strength of the MIG-welded AlMg 4.5 Mn butt welds increases significantly due to shot peening. After optimizitation of the peening parameters by double peening with steel and glass shot, the fatigue strength of the conventionally MIG-welded joints reaches the fatigue strength of the cold formed base material. The improvement is limited however on high numbers of load cycles. Fig. 7 shows the characteristic parameters of the surface layers after the shot peening processes. These parameters are effective in the improvement of the fatigue strength and include the distributions of the transverse and longitudinal compressive stresses and the higher surface hardness induced by shot peening. The distribution of the half width of the diffraction lines, dependent upon the hardness of the material, is also shown for comparison. Another additional reason for the extraordinary impro-

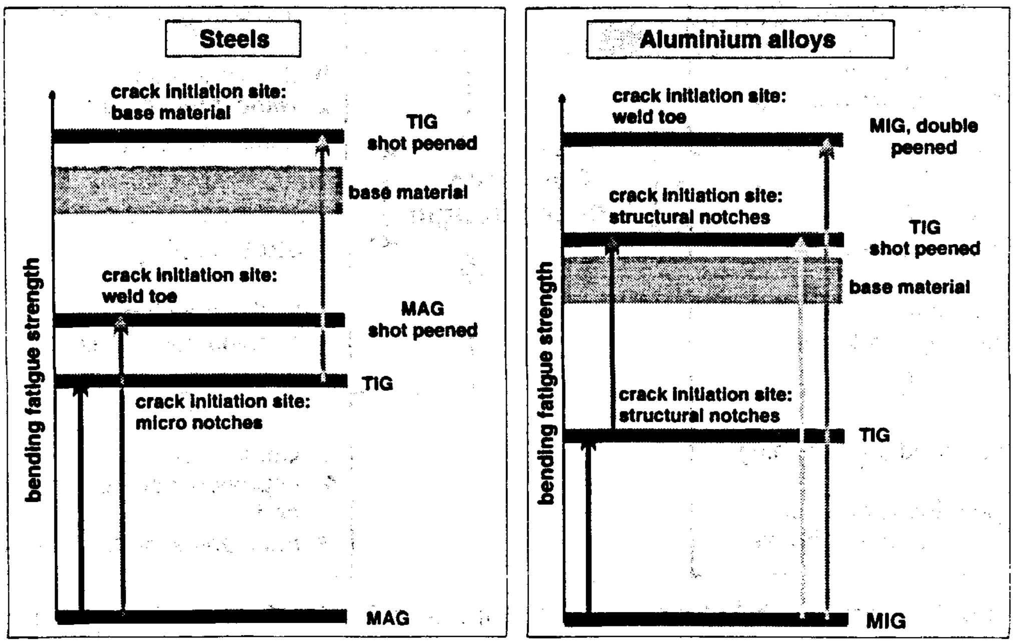

Figure 8: Influence of different welding and post-weld treatment methods on the crack initiation sites of high strength steels and high strength aluminium-alloys.

vement of the fatigue strength is that the sharpness of the notches at the weld toe could be reduced by the optimized shot peening process. The same effect, obviously possible only in the relatively soft Al-alloys, could be seen in welded joints of the age-hardened AlZn 4.5 Mg 1-alloy. The different efficiencies of the post-weld treatment methods in steels and Al-alloys are summarized in Fig. 8.

4. Conclusions

The results of the presented investigations are summarized in Fig. 9. It can be shown that an improvement in the fatigue strength of high strength steels and high strength Al-alloys can be realized first by an improvement of the weld seam profile with the consequence of a reduction of the notch sharpness at the weld toe. Then, a fatigue strength, higher than that of the conventionally MAW-, MAG or MIG-welded joints is possible but the fatigue strength of the base material can not be reached. The same improvement is possible through the application of shot peening. However, considering steels, the optimization of the fatigue strength, which is achieved when the fatigue strength of the welded joints reaches the fatigue strength of the base marterial, requires both methods. Only in Al- alloys double peening without TIG-dressing is so effective as to reach the optimum fatigue strength. If shot peening is used after an optimization of the weld seam geometry, the secondary effects as microscopic or structural notches and tensile residual stresses can be compensated for completely. Additionally it should be emphasized that shot peening or TIG-dressing of T-joints with root-imperfections is not advantageous, because the fatigue cracks will then start at the root passes and the fatigue strength will be the same as after conventional welding.

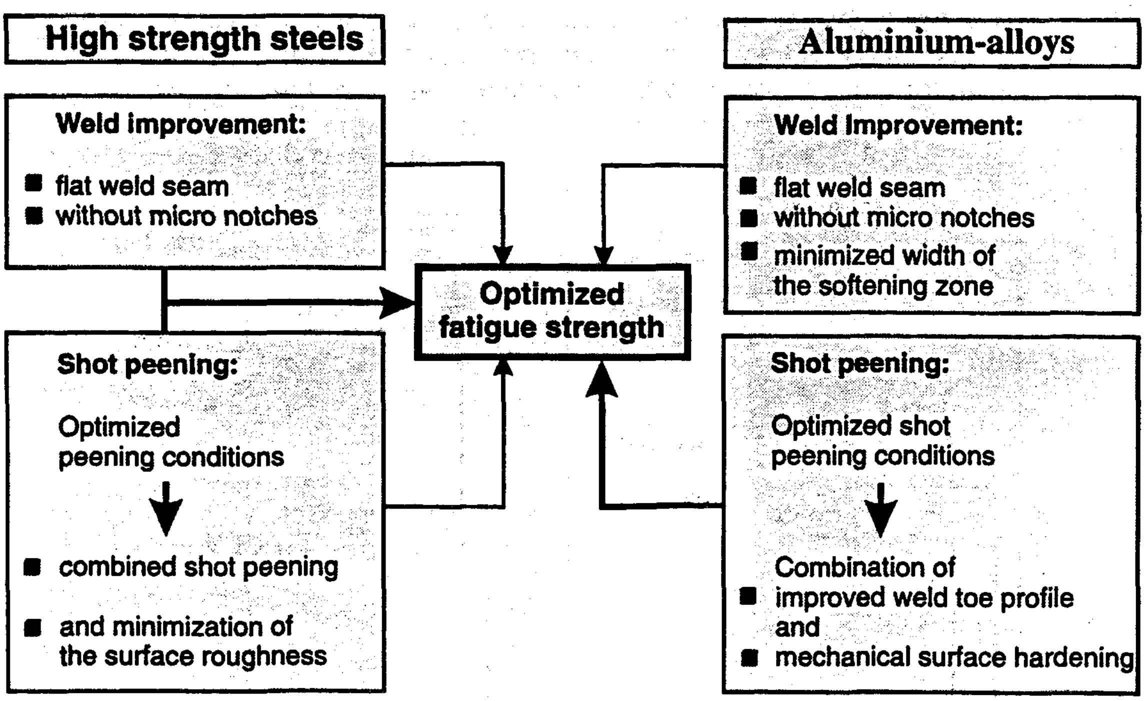

Figure 9: Requirements to be considered for improving the fatigue strength of welded joints of high strength steels and aluminium-alloys.

Furthermore, new investigations on AlMgSi 1-alloy /11,12/ show, that using TIG-AC- welding with superposition of high frequency pulses or mechanized TIG-DC-welding with negative polarization of the electrode and the use of helium as shielding gas, high welding velocities of approximately 1.2 m/min may be combined with an optimized weld seam geometry. The consequence is that the presented possibilties are also usuable under consideration of economical aspects, if a reduction in the weight of welded constructions is required.

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